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Flow-dominated plasma dynamics

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Most of the plasma dynamics in the universe not occurring in compact objects, like stars, is in a *flow-dominated* regime, in that encounters between plasma flows, or between plasmas and magnetic fields, solids, and/or neutral gases take place with sufficient velocity that kinetic energy dominates the dynamics of the interaction. This is in contrast to most laboratory plasma experiments, in which thermal or magnetic energy which dominates. Flow kinetic energy represents a potentially large, out-of-equilibrium energy reservoir can drive many nonlinear processes including fluid instabilities and turbulence, supersonic magnetic reconnection, and kinetic instabilities that can generate much higher densities and magnetic fields than predicted by fluid theory, drive non-thermal populations, and accelerate particles to relativistic energies.

The vast majority of cosmic plasma flows are highly super-magnetosonic and magnetized, with the in-flowing plasma having roughly equal parts thermal and magnetic energy ($\beta \sim 1$). In the rarefied plasmas of the interplanetary, interstellar, and intergalactic media, Coulomb collisions occur too infrequently to affect changes to the flow over observed flow transition time and length scales; collective effects and fields mediate the dynamics rather than Coulomb collisions, and the magnetic field plays a critical role in the evolution of structure. Conversion of flow kinetic energy to other forms is thought to play a large role in the overall partition of energy in the universe (i.e., the amount of energy contained in magnetic fields, fast particles, radiation, thermal distributions, kinetic energy, etc.). It has historically proven difficult to develop a full understanding of these physics using the limited amount of data available from observations and spacecraft, and fully kinetic 3D simulations that span the required length and time scales with realistic electron/ion mass ratios (which is thought to be required to fully capture the relevant physics [1]) are still beyond the capability of even the largest computing clusters. In recent years, there have been a number of laser-driven experiments that have made progress in producing flows with some (but not all) of the required dimensionless parameters, but reproducing the full set of physics thought to take place in cosmic shocks has still not been achieved.

High-energy-density plasmas are another area where the interplay of flow kinetic energy and plasma thermal/magnetic energy becomes important and non-obvious, as local heating of ions and equilibration with electrons has been suggested to foster streaming instabilities and/or modified shock structure. Even in highly collisional unmagnetized flow-dominated plasmas, such as those occurring in many inertial confinement fusion experiments, may enter regimes in which kinetic effects become significant when ion inertial length scales become comparable to Coulomb collision scales. This has been postulated to lead to species separation and variance of fuel composition in the hot-spot, which could lower the overall yields achieved.

In addition to cosmic and high-energy-density plasmas, many important technological applications of plasmas depend essentially on flow-dominated plasmas and kinetic energy

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conversion. Plasma propulsion for satellites and spacecraft is one such application that touches our day-to-day lives, as plasma thrusters are used to maintain the orbits of global communications satellites; plasma etching for semiconductor manufacturing relies on the efficient generation of plasma beam populations; and innovative pulsed approaches to magnetic fusion, such as magneto-inertial fusion, can rely on dynamics that are strongly magnetized and flow-dominated and in which the effects described above may become important.

Flow-dominated plasma dynamics represent an area of broad impact in both science and engineering. Key open questions include:

- What are the dynamics that give rise to the observed structure in cosmic flows?
- What are the mechanisms for energy conversion into and between the various channels mentioned above?
- How does the flow structure and energy partition change across parameter regimes and scale lengths?
- Can flow-dominated plasmas be used to convert energy to forms useful for plasma technology applications?

These topics are central to a number of the themes called out in a recent community report on research needs in fundamental plasma science [2], including many from Chapter 3 – "Understanding the energetics of the plasma universe" such as developing an understanding of the dynamics of energy coupling between flow energy, thermal, and magnetic in flow-dominated plasmas; the effects of energetic particle populations on their plasma environments (e.g., cosmic rays or fusion products); and the mechanisms of shock physics in magnetized plasmas.

In the past, the scope of basic plasma physics research has focused primarily on static systems, steady-state processes, and equilibrium plasma properties. This is understandable considering that the US basic plasma science program is stewarded by the Office of Science's office of Fusion Energy Sciences (OS-FES), which has a portfolio that is dominated by a fusion energy mission dedicated exclusively to pursuing pseudo-stead-state magnetic confinement concepts. However, developing a better understanding of the dynamics of flow-dominated plasmas could impact a number of communities including researchers typically funded by the NNSA (magnetically-driven inertial confinement fusion [3]), ARPA-E (magneto-inertial fusion, into which further research was recently endorsed by the JASON scientific advisory panel [4]), NASA (space propulsion, space/astrophysics [5, 6]), AFRL (space propulsion), NSF (fundamental plasma science), OS-FES (basic plasma science), and private industry (pulsed magnetic fusion, plasma technology applications). We feel that this broad appeal is strong motivation for increased investment in this topical area.

[1] Andr Balogh and Rudolf A. Treumann. *Physics of Collisionless Shocks*, volume 12 of *ISSI Scientific Report Series*. 2013.

[2] Panel on Frontiers of Plasma Science. Plasma: At the frontier of scientific discovery. Report, 2017.

[3] NNSA. 2016 inertial confinement fusion program framework. Report, 2016.

[4] JASON. Prospects for low cost fusion development. Report, The MITRE Corporation, 2018.

[5] Committee on a Decadal Strategy for Solar and Space Physics. Solar and space physics: A science for a technological society. Report, 2013.

[6] Committee for a Decadal Survey of Astronomy and Astrophysics. New worlds, new horizons in astronomy and astrophysics. Report, 2010.